EE101: BJT basics

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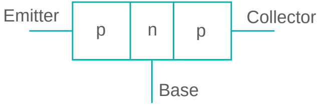
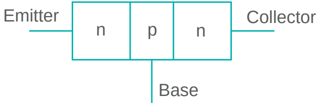
Indian Institute of Technology Bombay

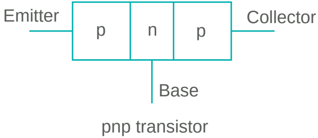
Bipolar Junction Transistors

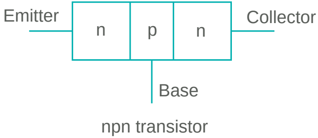


pnp transistor



npn transistor





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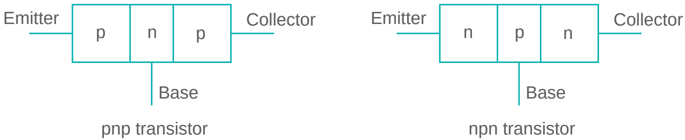
Bipolar Junction Transistors



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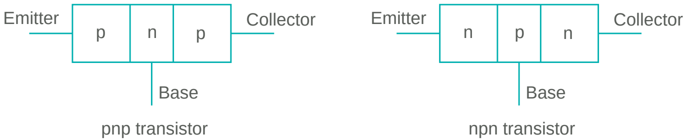

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* Transistor: "transfer resistor"

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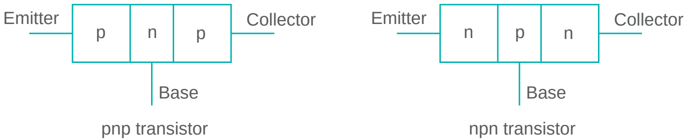

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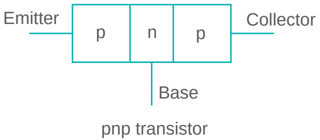

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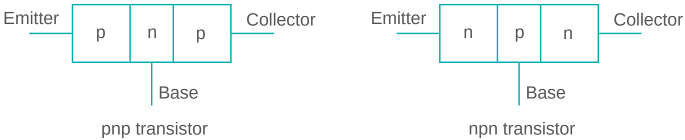

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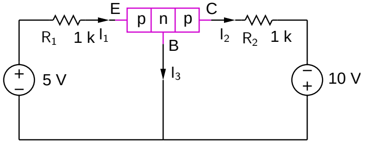
  WRONG! Let us see why.

Consider a *pnp* BJT in the following circuit:



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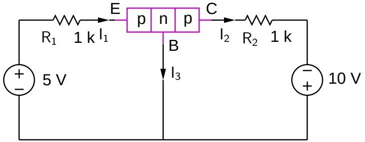
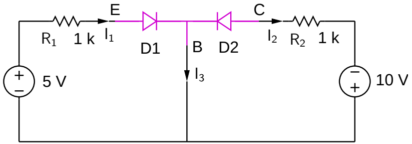


If the transistor is replaced with two diodes connected back-to-back, we get,



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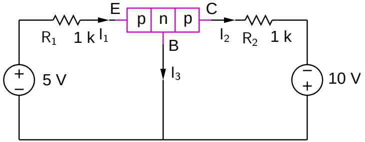

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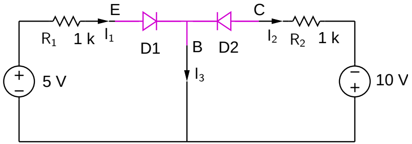


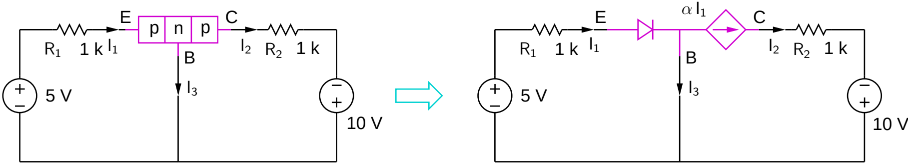
Assuming $V_{\text{on}} = 0.7\ V$ for D1, we get

$I_1 = \dfrac{5\ V - 0.7\ V}{R_1} = 4.3\ \text{m}A,$

$I_2 = 0$ (since D2 is reverse biased), and

$I_3 \approx I_1 = 4.3\ \text{m}A.$

Using a more accurate equivalent circuit for the BJT, we obtain,



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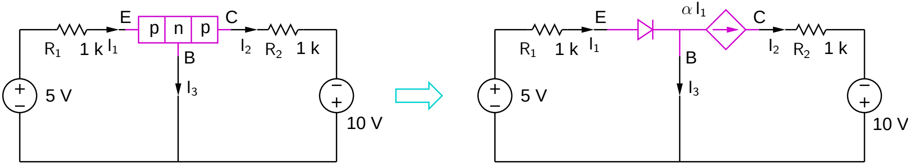

We now get,

$$I_1 = \frac{5\ V - 0.7\ V}{R_1} = 4.3\ \text{m}A\ \text{(as before)},$$

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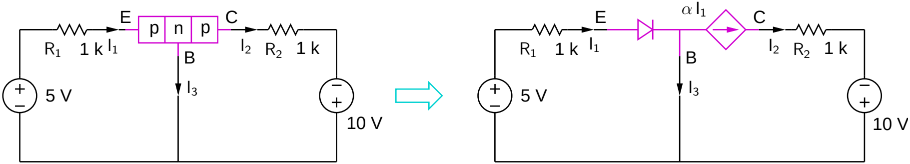

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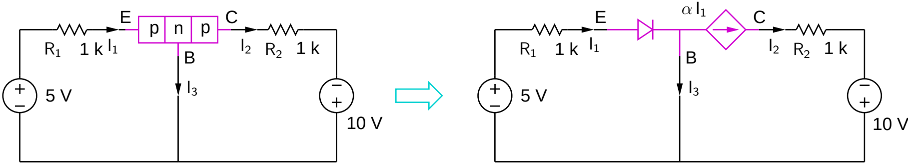

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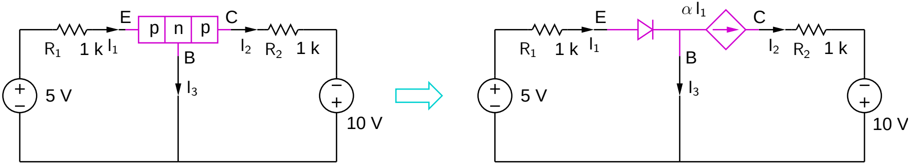

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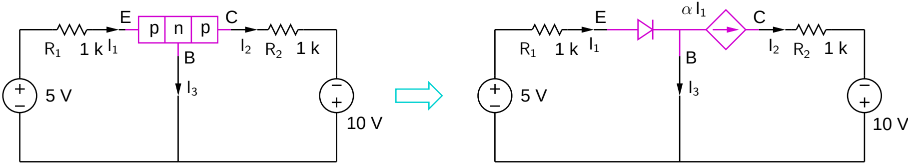

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Conclusion: A BJT is NOT the same as two diodes connected back-to-back (although it does have two *p*-*n* junctions).

What is wrong with the two-diode model of a BJT?

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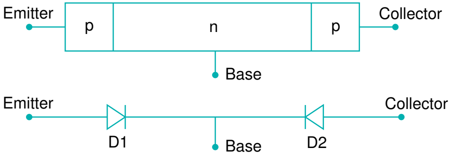
* When we replace a BJT with two diodes, we assume that there is no interaction between the two diodes, which may be expected if they are "far apart."



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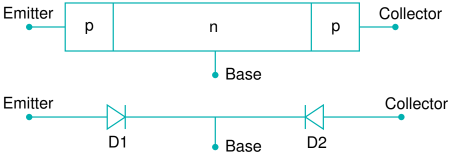
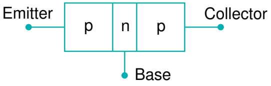


* However, in a BJT, exactly the opposite is true. For a higher performance, the base region is made as short as possible (subject to certain constraints), and the two diodes therefore cannot be treated as independent devices.



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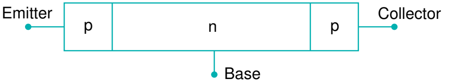

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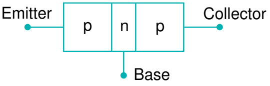
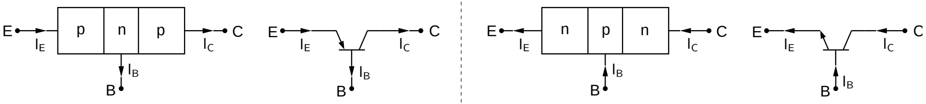


* Later, we will look at the "Ebers-Moll model" of a BJT, which is a fairly accurate representation of the transistor action.

BJT in active mode



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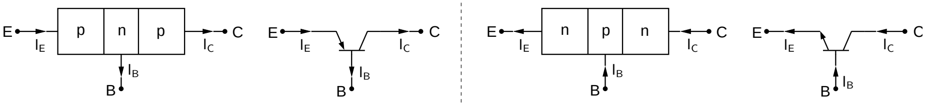

* In the active mode of a BJT, the B-E junction is under forward bias, and the B-C junction is under reverse bias.
  - For a *pnp* transistor, $V_{EB} > 0\ V$, and $V_{CB} < 0\ V$.
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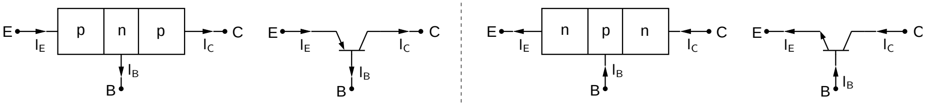

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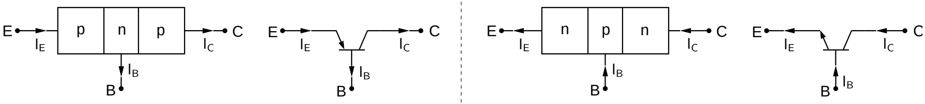

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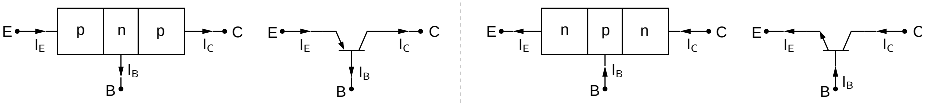

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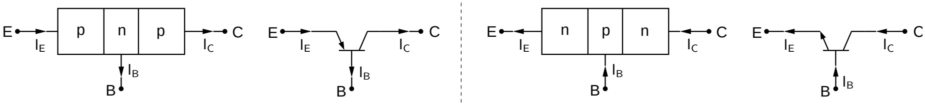

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* The symbol for a BJT includes an arrow for the emitter terminal, its direction indicating the current direction when the transistor is in active mode.
* Analog circuits, including amplifiers, are generally designed to ensure that the BJTs are operating in the active mode.

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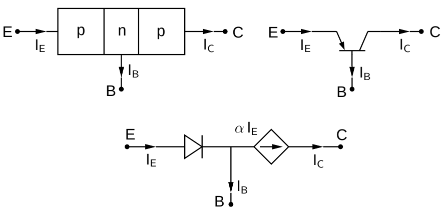

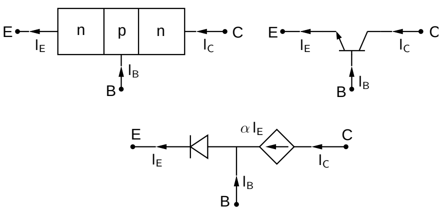

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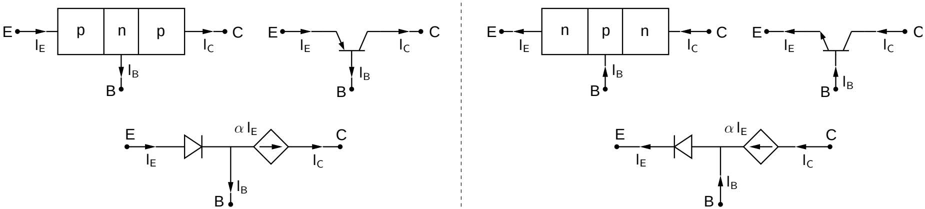

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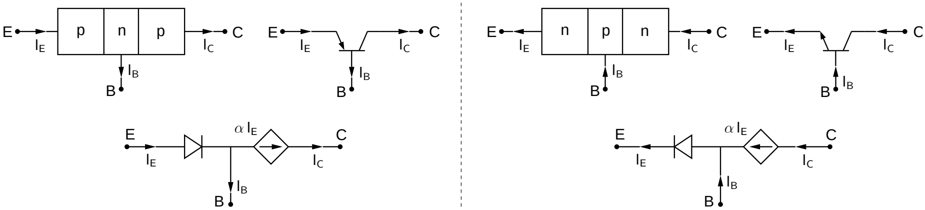

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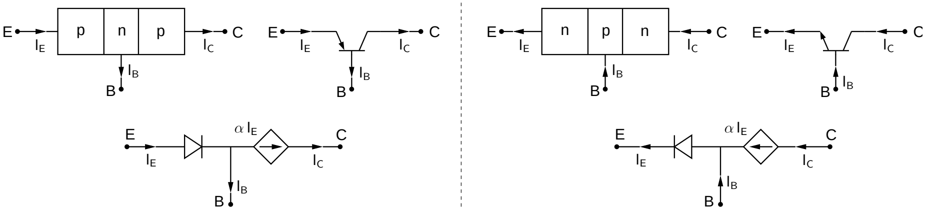

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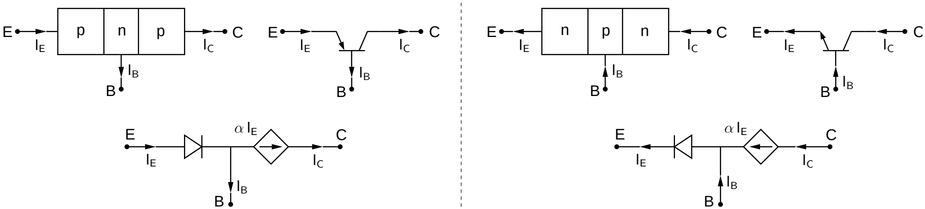

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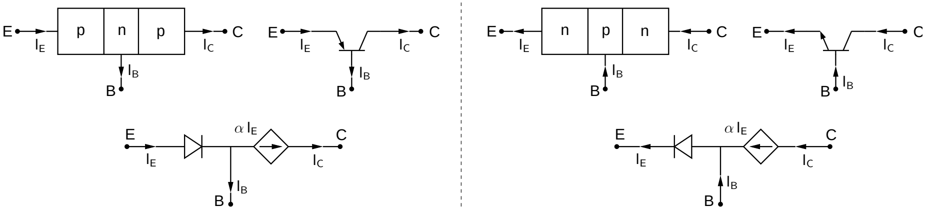
$$\beta = \frac{I_C}{I_B} = \frac{\alpha}{1-\alpha}\,.$$

* β is a function of I_C and temperature. However, we will generally treat it as a constant, a useful approximation to simplify things and still get a good insight.

BJT in active mode



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α	β
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0.95	19
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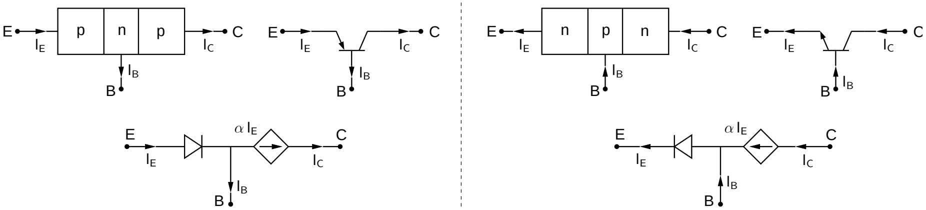
BJT in active mode



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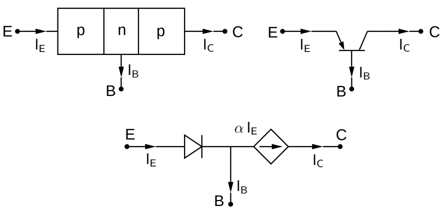

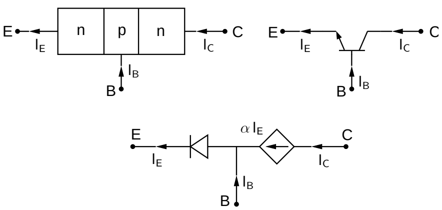

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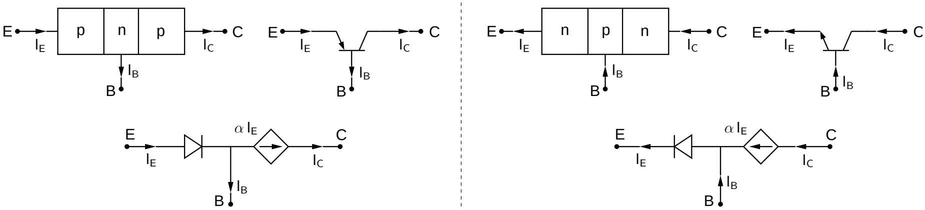

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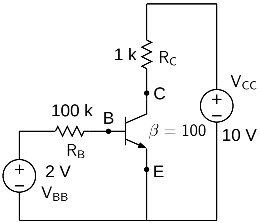
* A large $\beta \Rightarrow I_B \ll I_C$ or I_E when the transistor is in the active mode.

A simple BJT circuit



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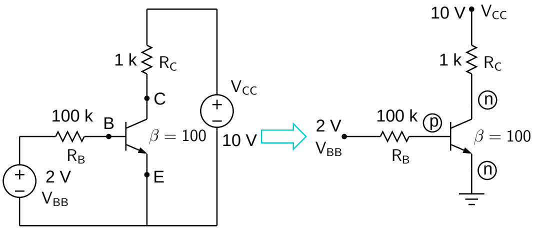
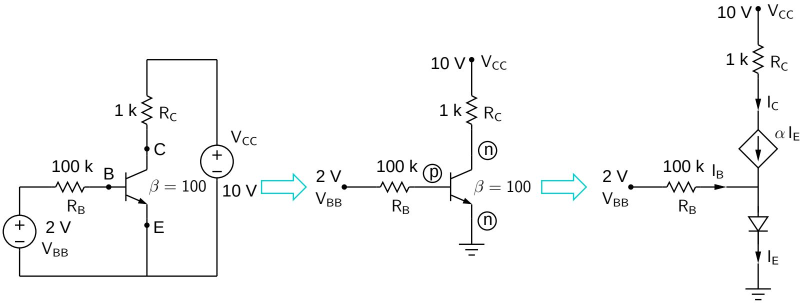


A simple BJT circuit



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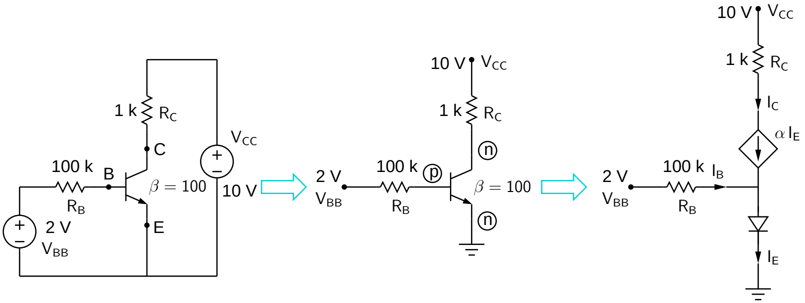

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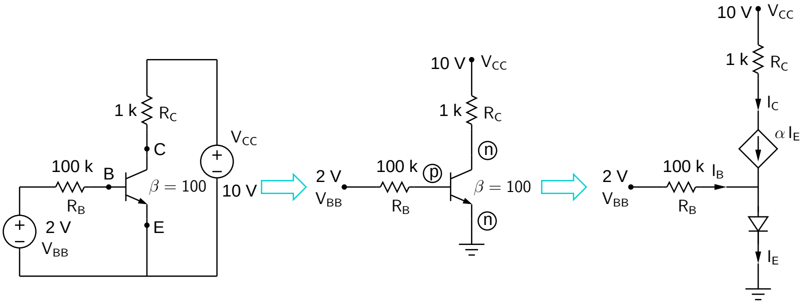

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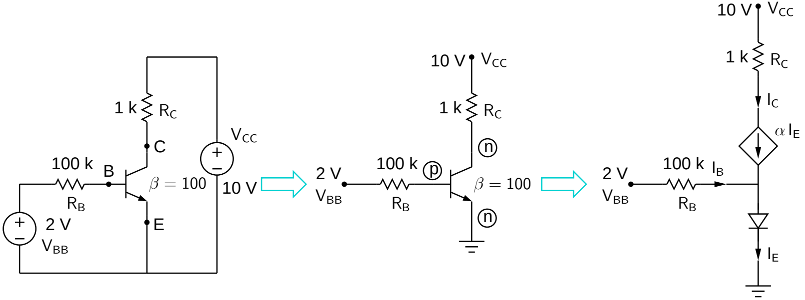

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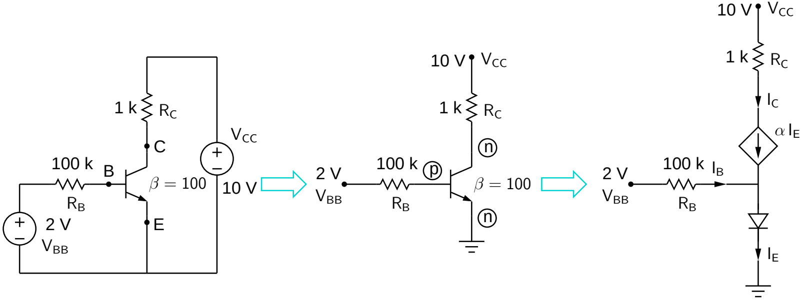

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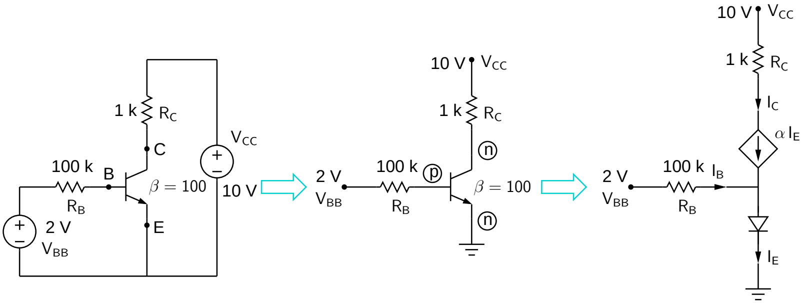

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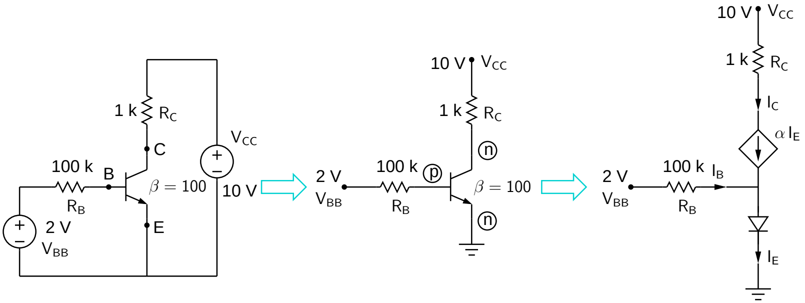

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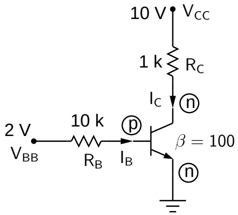
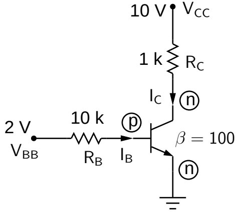
$$V_{BC} = V_B - V_C = 0.7\ V - 8.7\ V = -8.0\ V\,,$$

i.e., the B-C junction is indeed under reverse bias.

A simple BJT circuit (continued)



What happens if R_B is changed from 100 k to 10 k?



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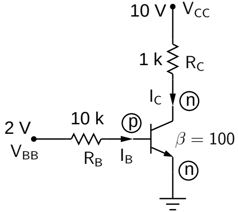

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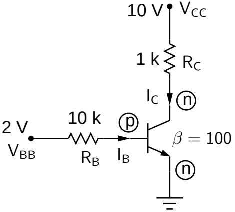

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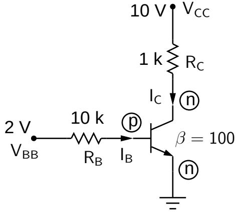

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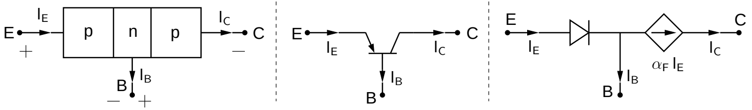
V_{BC} is not only positive, it is *huge*!

The BJT cannot be in the active mode, and we need to take another look at the circuit.

Ebers-Moll model for a *pnp* transistor

Active mode ("forward" active mode): B−E in f. b., B−C in r. b.



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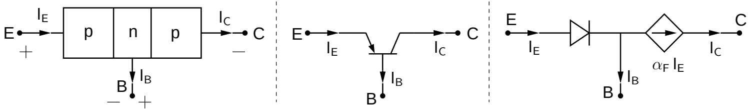

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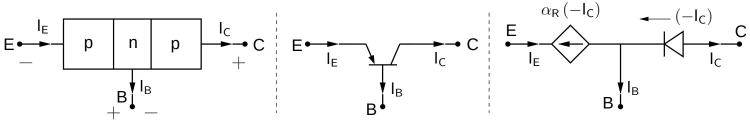

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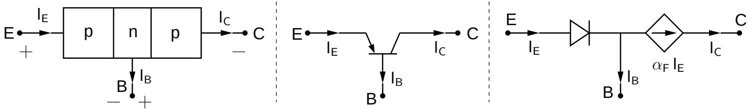

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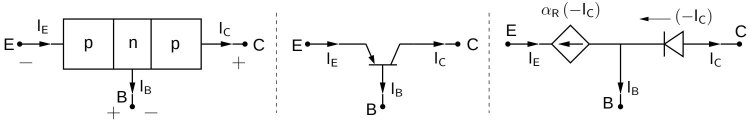

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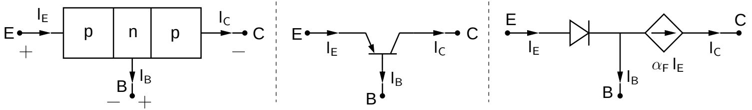

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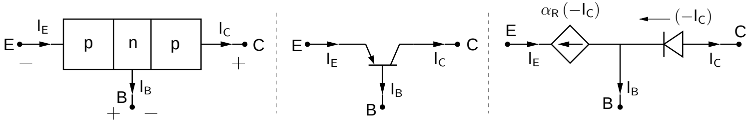

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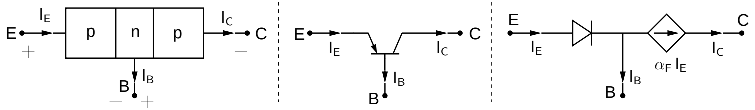

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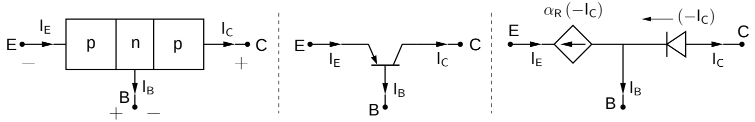

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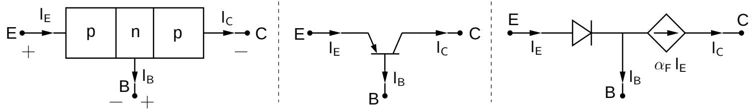

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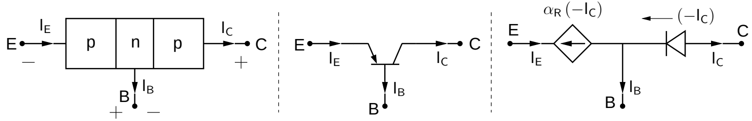

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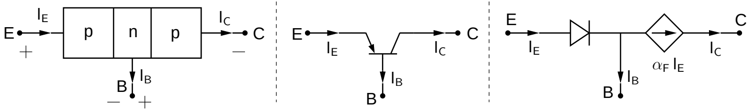

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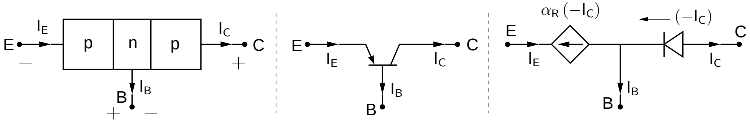

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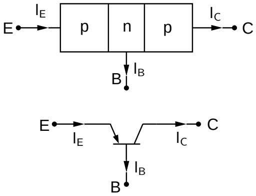
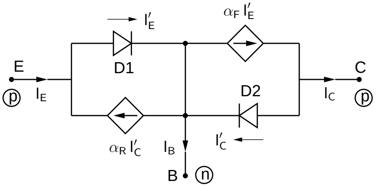
In amplifiers, the BJT is biased in the forward active mode (simply called the "active mode") in order to make use of the higher value of β in that mode.

Ebers-Moll model for a *pnp* transistor

The Ebers-Moll model combines the forward and reverse operations of a BJT in a single comprehensive model.





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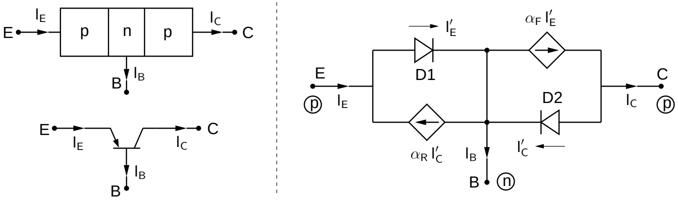

The currents I'_E and I'_C are given by the Shockley diode equation:

$$I'_E = I_{ES}\left[\exp\left(\frac{V_{EB}}{V_T}\right) - 1\right], \quad I'_C = I_{CS}\left[\exp\left(\frac{V_{CB}}{V_T}\right) - 1\right].$$

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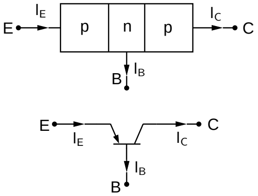

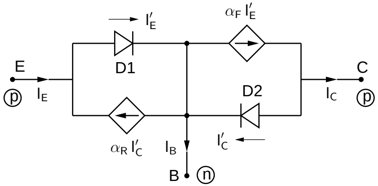

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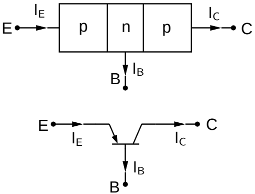
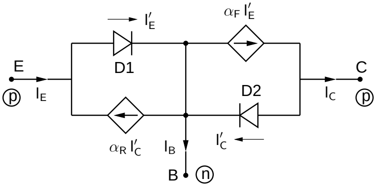
Mode	B-E	B-C	
Forward active	forward	reverse	$I'_E \gg I'_C$
Reverse active	reverse	forward	$I'_C \gg I'_E$
Saturation	forward	forward	I'_E and I'_C are comparable.
Cut-off	reverse	reverse	I'_E and I'_C are negliglbe.

Ebers-Moll model

pnp transistor





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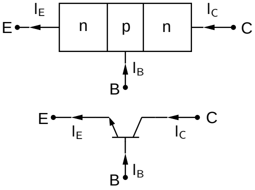
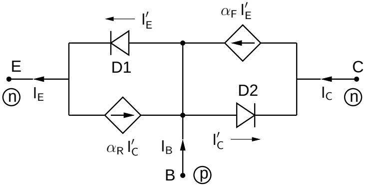
npn transistor





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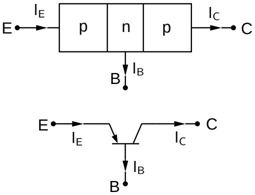

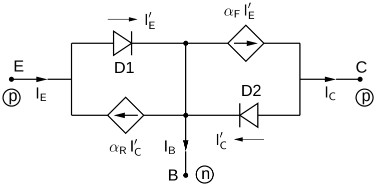

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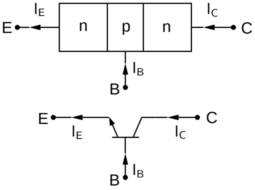

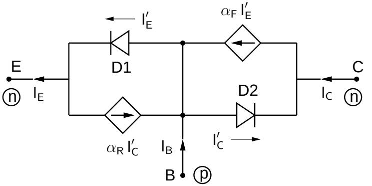

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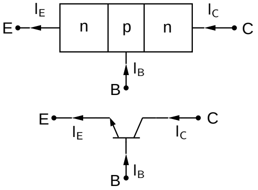
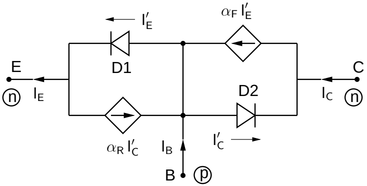
For an *npn* transistor, the same model holds with current directions and voltage polarities suitably changed.

I_C-V_{CE} characteristics





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$\alpha_F = 0.99, \quad I_{SE} = 1 \times 10^{-14}$ A

$\alpha_R = 0.50, \quad I_{SC} = 2 \times 10^{-14}$ A

A BJT is a three-terminal device, and its I-V chatacteristics can therefore be represented in several different ways. The I_C versus V_{CE} characteristics are very useful in amplifiers.

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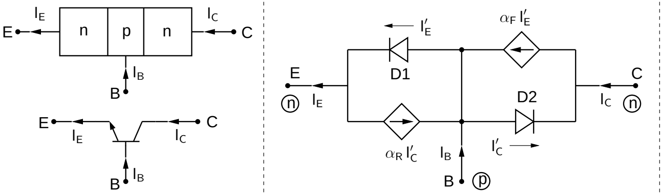

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To start with, we consider a single point, $I_B = 10\,\mu A$, $V_{CE} = 5\,V$.

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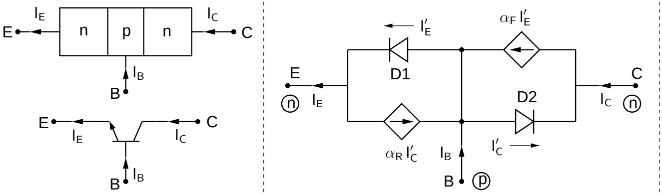

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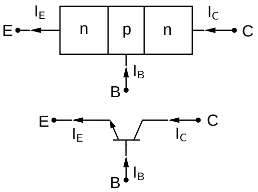
A BJT is a three-terminal device, and its *I*-*V* chatacteristics can therefore be represented in several different ways. The I_C versus V_{CE} characteristics are very useful in amplifiers.

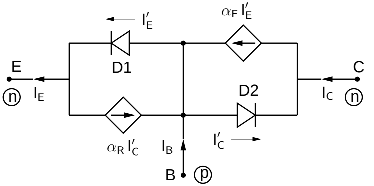
To start with, we consider a single point, $I_B = 10\,\mu A$, $V_{CE} = 5\,V$.

There are several ways to assign V_{BE} and V_{CB} so that they satisfy the constraint:

$V_{CB} + V_{BE} = (V_C - V_B) + (V_B - V_E) = V_{CE} = 5\,V$.

I_C-V_{CE} characteristics





$I'_E = I_{ES}\,[\exp(V_{BE}/V_T) - 1]$

$I'_C = I_{CS}\,[\exp(V_{BC}/V_T) - 1]$

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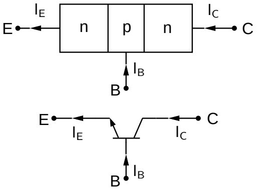
To start with, we consider a single point, $I_B = 10\,\mu A$, $V_{CE} = 5\,V$.

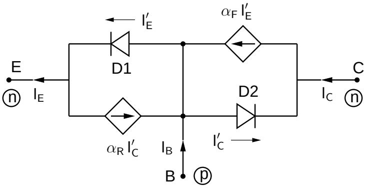
There are several ways to assign V_{BE} and V_{CB} so that they satisfy the constraint:

$V_{CB} + V_{BE} = (V_C - V_B) + (V_B - V_E) = V_{CE} = 5\,V$.

Let us consider some of these possibilities.

I_C-V_{CE} characteristics





$$I'_E = I_{ES}\,[\exp(V_{BE}/V_T) - 1]$$

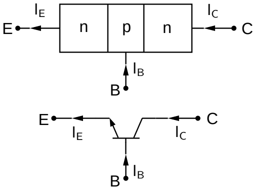
$$I'_C = I_{CS}\,[\exp(V_{BC}/V_T) - 1]$$

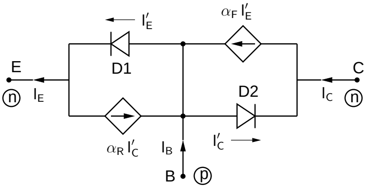
$$\alpha_F = 0.99, \quad I_{SE} = 1 \times 10^{-14}\ \mathrm{A}$$

$$\alpha_R = 0.50, \quad I_{SC} = 2 \times 10^{-14}\ \mathrm{A}$$

Constraints: $I_B = 10\,\mu A$, $V_{CE} = 5\,V$.

I_C-V_{CE} characteristics





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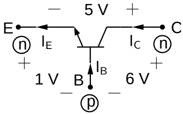
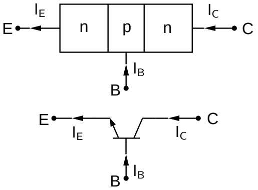
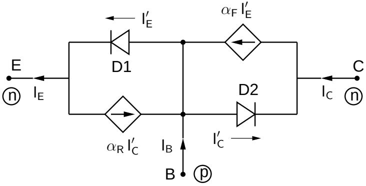


I_C-V_{CE} characteristics





$$I'_E = I_{ES}\ [\exp(V_{BE}/V_T) - 1]$$

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$\alpha_F = 0.99$, $I_{SE} = 1 \times 10^{-14}$ A

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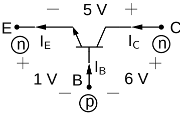
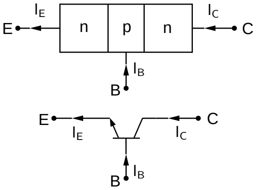
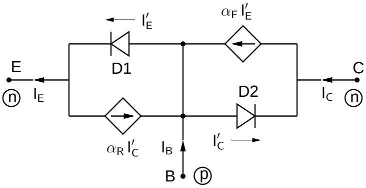
Constraints: $I_B = 10\,\mu A$, $V_{CE} = 5\,V$.



D1 and D2 are both off, and we cannot satisfy the condition, $I_B = 10\,\mu A$, since all currents are much smaller than $10\,\mu A$.

I_C-V_{CE} characteristics





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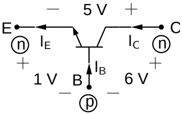
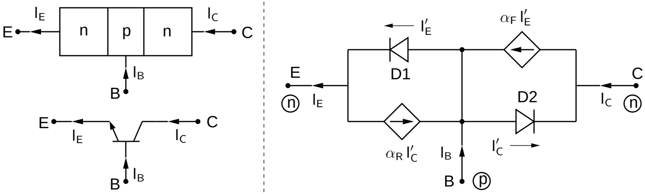


D1 and D2 are both off, and we cannot satisfy the condition, $I_B = 10\,\mu A$, since all currents are much smaller than $10\,\mu A$.

$\Rightarrow$ This possibility (and similarly others with both junctions reverse biased) is ruled out.

I_C-V_{CE} characteristics



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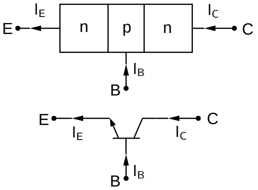
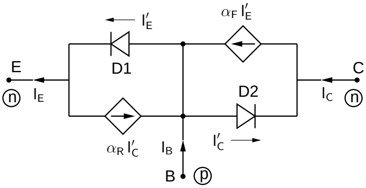
Constraints: $I_B = 10\,\mu A,\ V_{CE} = 5\ V.$

I_C-V_{CE} characteristics





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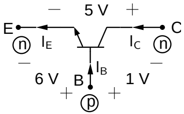
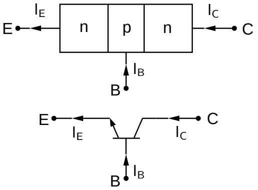
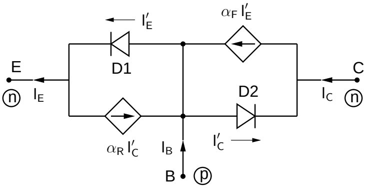


I_C-V_{CE} characteristics





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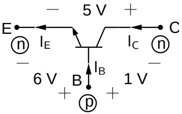
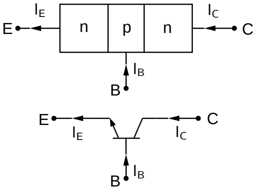
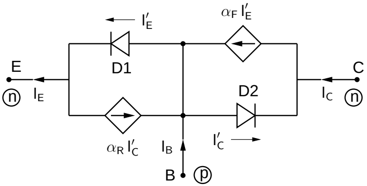


D1 and D2 are both conducting; however, the forward bias for the B-E junction is impossibly large.





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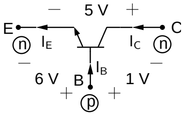
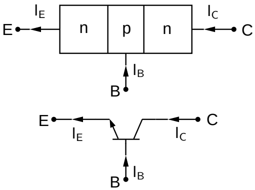
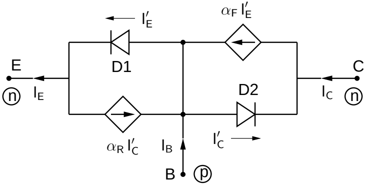


D1 and D2 are both conducting; however, the forward bias for the B-E junction is impossibly large.

$\Rightarrow$ This possibility is also ruled out.

I_C-V_{CE} characteristics





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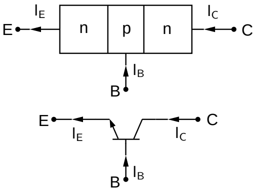

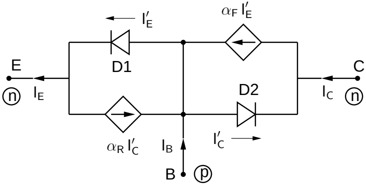

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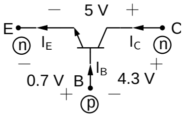
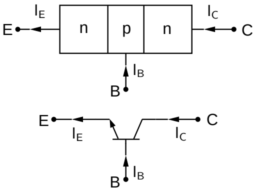
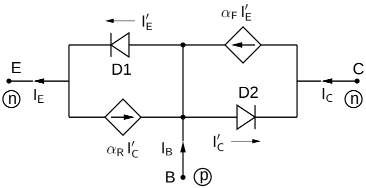


I_C-V_{CE} characteristics





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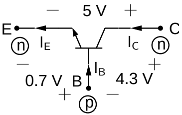
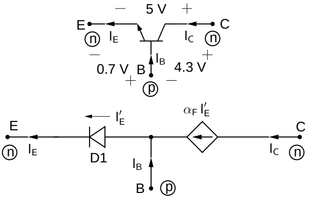


D1 is on, D2 is off. This is a realistic possibility. Since the B-C junction is under reverse bias, I'_C and $\alpha_R I'_C$ are much smaller than I'_E, and therefore the lower branches in the Ebers-Moll model can be dropped (see next slide).

I_C-V_{CE} characteristics

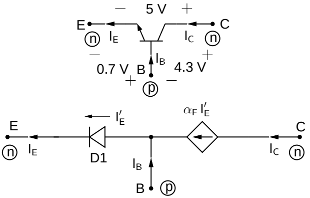


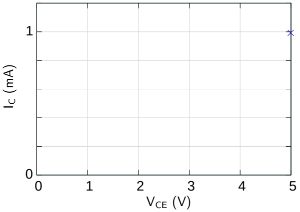
(The actual values for V_{BE} and V_{CB} obtained by solving the Ebers-Moll equations are $V_{BE} = 0.656\ V$ and $V_{CB} = 4.344\ V$.)

The BJT is in the active mode, and therefore

$$I_C = \beta\, I_B = \frac{\alpha_F}{1-\alpha_F}\, I_B = 99 \times 10\,\mu A = 0.99 \text{ mA}.$$

I_C-V_{CE} characteristics





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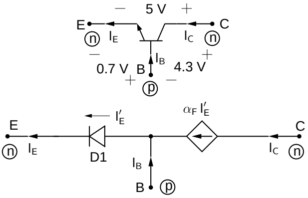
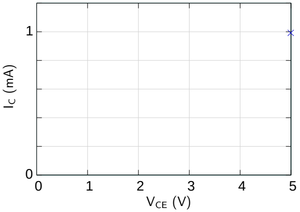
I_C-V_{CE} characteristics





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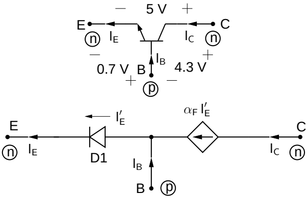
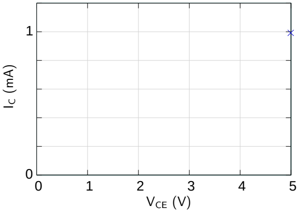
The BJT is in the active mode, and therefore

$$I_C = \beta\, I_B = \frac{\alpha_F}{1-\alpha_F}\, I_B = 99 \times 10\,\mu A = 0.99 \text{ m}A.$$

If V_{CE} is reduced to, say, 4 V, and I_B kept at $10\,\mu A$, our previous argument holds, and once again, we find that $I_C = \beta\, I_B = 0.99$ mA.

I_C-V_{CE} characteristics





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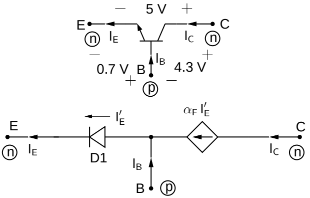
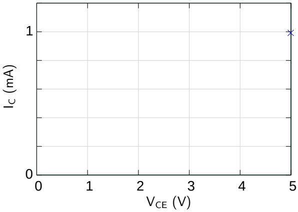
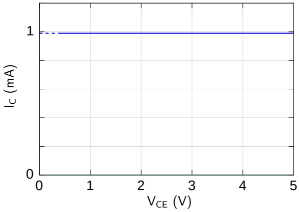
If V_{CE} is reduced to, say, 4 V, and I_B kept at $10\,\mu A$, our previous argument holds, and once again, we find that $I_C = \beta\, I_B = 0.99$ mA.

Thus, the plot of I_C versus V_{CE} is simply a horizontal line.

I_C-V_{CE} characteristics







(The actual values for V_{BE} and V_{CB} obtained by solving the Ebers-Moll equations are $V_{BE} = 0.656\ V$ and $V_{CB} = 4.344\ V$.)

The BJT is in the active mode, and therefore

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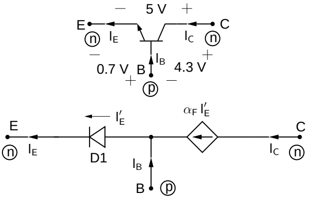
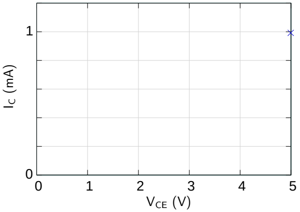
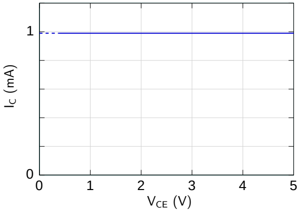
If V_{CE} is reduced to, say, 4 V, and I_B kept at $10\,\mu A$, our previous argument holds, and once again, we find that $I_C = \beta\, I_B = 0.99$ mA.

Thus, the plot of I_C versus V_{CE} is simply a horizontal line.

I_C-V_{CE} characteristics







(The actual values for V_{BE} and V_{CB} obtained by solving the Ebers-Moll equations are $V_{BE} = 0.656\ V$ and $V_{CB} = 4.344\ V$.)

The BJT is in the active mode, and therefore

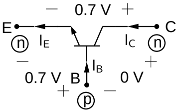
$$I_C = \beta\, I_B = \frac{\alpha_F}{1-\alpha_F}\, I_B = 99 \times 10\,\mu A = 0.99\ \text{m}A.$$

If V_{CE} is reduced to, say, $4\ V$, and I_B kept at $10\,\mu A$, our previous argument holds, and once again, we find that $I_C = \beta\, I_B = 0.99$ mA.

Thus, the plot of I_C versus V_{CE} is simply a horizontal line.

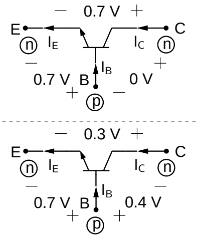
However, as $V_{CE} \rightarrow 0\ V$, things change (see next slide).

I_C-V_{CE} characteristics



When $V_{CE} \approx 0.7\,V$ (and I_B kept at $10\,\mu A$), the B-C drop is about $0\,V$.

I_C-V_{CE} characteristics



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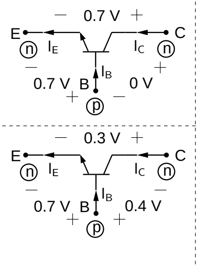
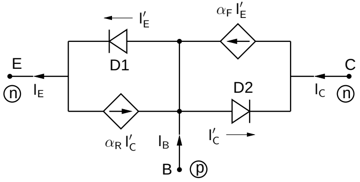
As V_{CE} is reduced further, the B-C junction gets forward biased. For example, with $V_{CE} = 0.3\,V$, we may have a voltage distribution shown in the figure.

(The numbers are only representative; the actual V_{BE} and V_{BC} values can be obtained by solving the E-M equations.)

I_C-V_{CE} characteristics





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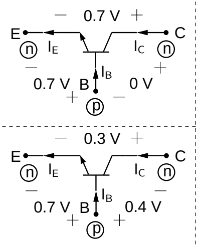

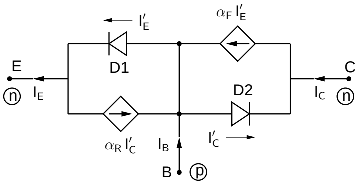

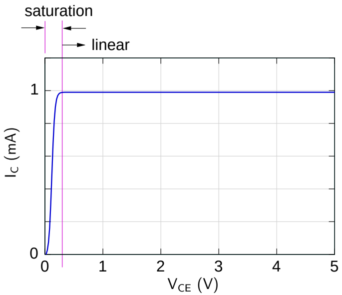

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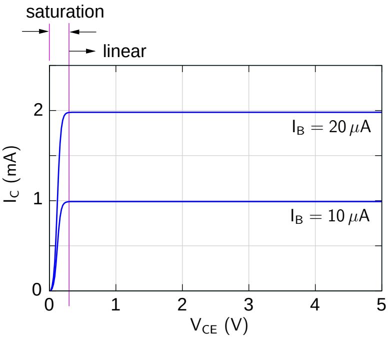
Now, the component I'_C in the E-M model becomes significant, $I_C = \alpha_F I'_E - I'_C$ reduces, and I_C becomes smaller than βI_B.

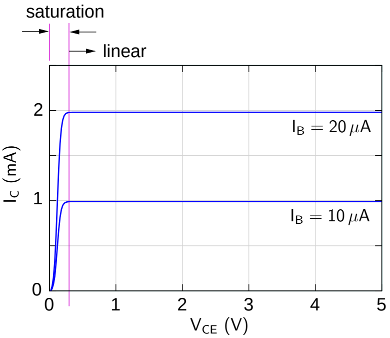
The region where $I_C < \beta I_B$ is called the "saturation region."

I_C-V_{CE} characteristics



If I_B is doubled (from $10\,\mu A$ to $20\,\mu A$), $I_C = \beta I_B$ changes by a factor of 2 in the linear region. Apart from that, there is no qualitative change in the $I_C - V_{CE}$ plot.

I_C-V_{CE} characteristics



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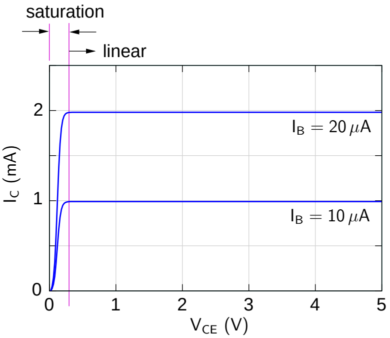
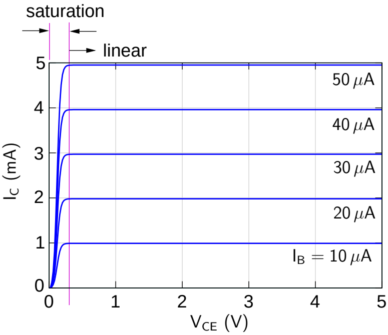
Clearly, the $I_C - V_{CE}$ behaviour of a BJT is not represented by a single curve but by a *family* of curves, known as the "$I_C - V_{CE}$ characteristics."

I_C-V_{CE} characteristics





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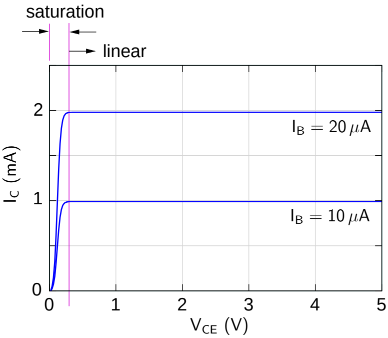

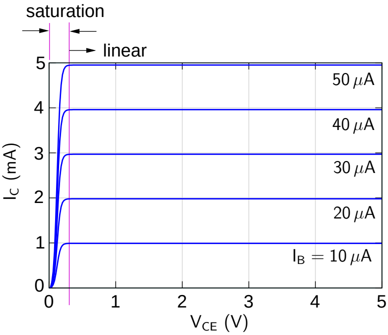

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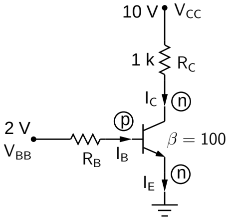
The $I_E - V_{CB}$ and $I_C - V_{BE}$ characteristics of a BJT are also useful in understanding BJT circuits.

A simple BJT circuit (revisited)



We are now in a position to explain what happens when R_B is decreased from 100 k to 10 k in the above circuit.

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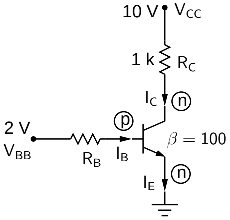

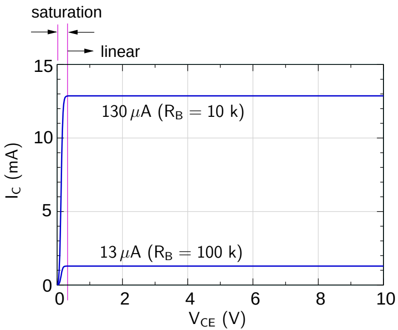

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Let us plot $I_C - V_{CE}$ curves for $I_B \approx \dfrac{V_{BB} - 0.7\ V}{R_B}$ for the two values of R_B.

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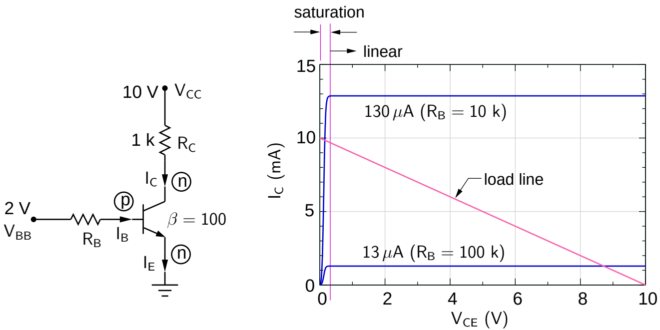

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In addition to the BJT $I_C - V_{CE}$ curve, the circuit variables must also satisfy the constraint, $V_{CC} = V_{CE} + I_C R_C$, a straight line in the $I_C - V_{CE}$ plane.

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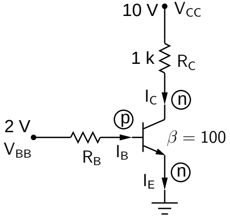

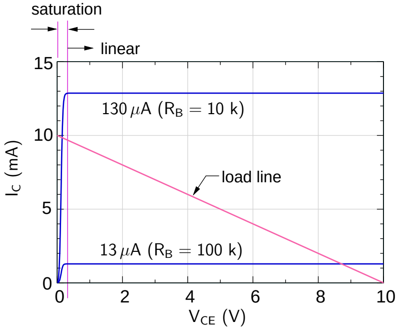

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The intersection of the load line and the BJT characteristics gives the solution for the circuit. For $R_B = 10$ k, note that the BJT operates in the saturation region, leading to $V_{CE} \approx 0.2\,V$, and $I_C = 9.8$ mA.